



# VIBROACOUSTIC DIAGNOSTICS OF PRECISION MACHINING PARTS MADE OF HARD-TO-CUT MATERIALS USING CUTTING TOOL EQUIPPED WITH HARD CERAMICS

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## ABSTRACT

In present paper, the principles of vibroacoustic diagnostics of precision machining parts made of hard-to-cut materials using cutting tools with ceramic cutting element are described. The series of experiments show the sensitivity of vibroacoustic signal to the cutting process parameters variation. The block diagram of newly designed information measuring unit used for implementation of vibroacoustic diagnostic principles in precision machining is provided.

**Keywords:** diagnostics, vibroacoustic signal, ceramic cutting tool, product quality.

## INTRODUCTION

Until recently, the finishing treatment of hardened steels and heat-resistant alloys was performed with grinding operation. The technological characteristics of grinding are excessive heat and force load frequently causing the structural changes and tensile stresses within the surface layer of the workpiece. The practical experience shows that the grinding process is the main source of technological defects like burns on the workpiece surface. Due to use of innovative materials for cutting tools, increase of vibration resistance and accuracy of machine tools, the high-speed cutting machining becomes a good alternative to the grinding [1].

The advanced material for cutting tools used in finishing machining of hardened steels and heat-resistant alloys is ceramics which has high hardness, phase stability and wear-resistance in a wide range of temperatures and provides applicability of precision machining with up to 9-10 degree of fineness. However, even the most advanced grades of ceramics have relatively low crack-resistance causing the unpredictable brittle fracture of the cutting edge during different stages of operational period of the cutting tool and limiting a more extensive use of this type of material [2, 3]. Whereas for hardened steels machining the cutting machining has already been applied under some manufacturing conditions, the potential of finishing cutting of complex-shaped parts made of heat-resistant titanium and nickel alloys using ceramic cutting tools is not completely fulfilled [4]. The analysis of recent investigations of world's leading machine tools manufacturers shows that this research trend is a high-priority task.

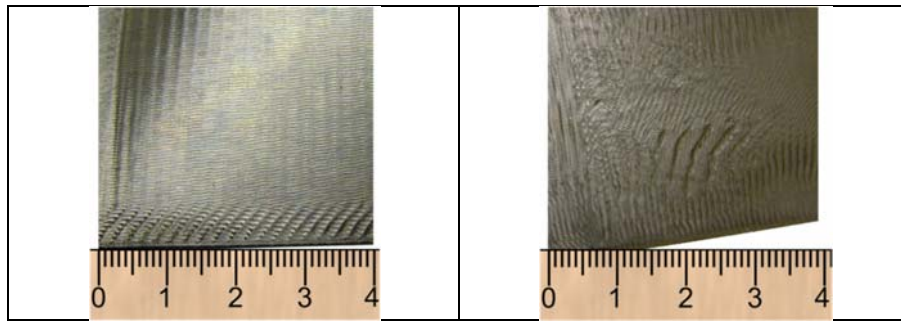
To increase the real-time reliability of precise CNC-machining the parts made of difficult-to-cut materials, the diagnostics systems for the manufacturing system conditions can be used. During use of the

manufacturing system, the diagnostics depending on the type of machining operation performs different tasks as follows: in roughing and semifinishing, the functional failures caused by brittle fracture or extremely gross wear of the cutter must be detected. At the same time, in finishing machining, the parametric reliability of the manufacturing system shall be provided, while the output disturbance, i.e. divergence of the part quality indicators, shall be prevented during machining process and not after machining completion.

Nowadays, the leading world's manufacturers start to produce ceramic milling cutters for multiaxis precise machining of air compressors and turbine motors providing increase of cutting speed up to 10 times as compared with use of solid carbide cutting tools and eliminating the above-mentioned technological defects of the grinding operation.

## GOALS AND SOLUTION

However, despite the good perspectives of finishing milling with the ceramic mills, there is still a number of problems that cannot be solved without application of diagnostic systems. In addition to the functional failures caused by brittle fracture, there is a precision part surface quality assurance. Milling process of parts having complex form surfaces is characterized by unstable conditions including low manufacturing stiffness, vibrations etc., which are worsened by specific properties of a difficult-to-cut materials and susceptibility of ceramics to the brittle fracture, that in aggregate often leads to the specific defects in the form of waviness (Figure-1, a) and notches, i.e. deep damages of the surface layer (Figure-1, b). These defects are unacceptable for the precise parts and cause the rejection of the production run, or may require additional machining operations to remove this defected layer.

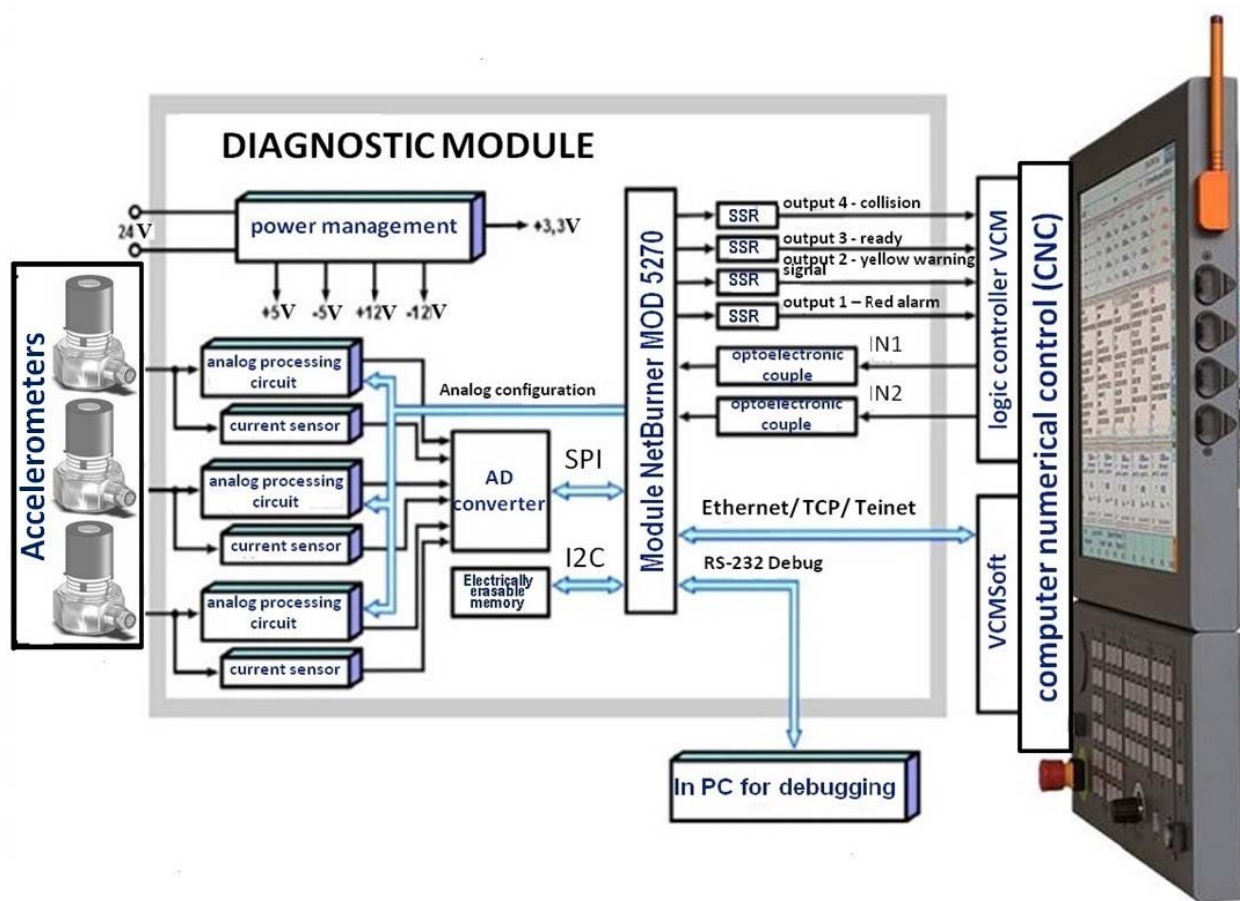


**Figure-1.** Specific defects on the surface of turbine blade made of heat-resistant alloy after the milling: waviness (a) and surface layer damages in the form of notches (b).

In this situation, the reduction of vibration impact for the manufacturing system as well as the use of vibroacoustic signals for diagnostics of machining precise parts made of difficult-to-cut materials are required. Using only the force parameters for the diagnostics of manufacturing system operating under very unstable conditions is less efficient because that approach has a relatively long response time due to the diagnostic parameter to be mathematically treated over its period of change. For precision machining parts having a complex-shape surface made of difficult-to-cut materials using

ceramic cutting tool, the vibroacoustic diagnostics by accelerometers sensible to vibrations generated by the cutting process is advantageous.

To implement the principles of vibroacoustic diagnostics of precision machining parts made of difficult-to-cut materials using ceramic cutting tool, a multifunctional information measuring system based on the three-axis milling CNC machine DMC 635V Ecoline at MSUT "STANKIN" was designed. The block diagram of this system is shown in Figure-2.



**Figure-2.** Block diagram of information measuring system based on the vibroacoustic diagnostics unit.



The designed system is build on the diagnostic module VCM DAQ Unit working in real-time mode and analyzing the vibration parameters to prevent the sudden falls of cutting tools or parts being machined. The system is designed in such a way as to allow the operator to recognize potential problems and assume the preventive actions in time.

The vibroacoustic diagnostic unit is assembled inside the electrical cabinet of the machine tool. The unit consists of data processor receiving the signal from the accelerometers and converting it to the serial digital signals being analyzed by specialized software connected to the CNC unit of the machine tool.

It should be made clear that the functionality of this unit is not limited by vibration diagnostics, but allows making a complex monitoring of the manufacturing system conditions by the means of different types of signals arising in the cutting area and recorded with measuring equipped installed on the machine tool, i. e. power sensor and piezoelectric dynamometer.

The signal received from the accelerometers is proportional to vibration acceleration. To estimate the influence of vibrations to the form accuracy of the machined part, the vibration displacement shall be used. It indicates the maximum displacement range of the controlled point during the vibration process and is characterized by the pick-to-pick amplitude.

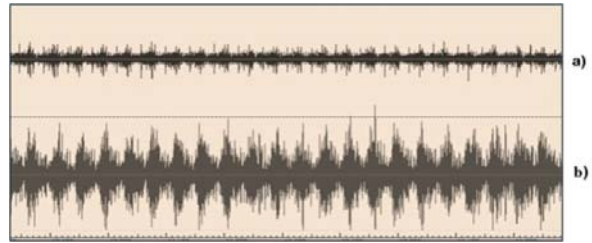
If the vibration acceleration amplitude requires conversion to the vibration displacement amplitude, the following equation can be used:

$$A = \frac{Aa}{\omega^2}, \quad (1)$$

where  $Aa$  is the vibration acceleration amplitude,  $A$  - vibration displacement amplitude,  $\omega$  – rotational frequency which is equal to  $2\pi f$  ( $f$  is the vibration frequency, Hz).

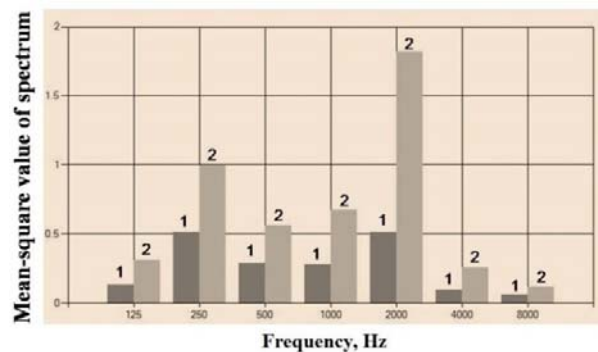
## EXPERIMENTAL STUDY OF VIBROACOUSTIC SIGNALS

In Figure-3, a characteristic waveform of vibroacoustic signal when conventional milling using the sharpened cutter with ceramic inserts (Figure-2, a) and using a cutter with flank wear about 0.2 mm (Figure-2, b) are shown. It can be seen that the amplitude of the signal describing the milling using a worn cutter is significantly increased.



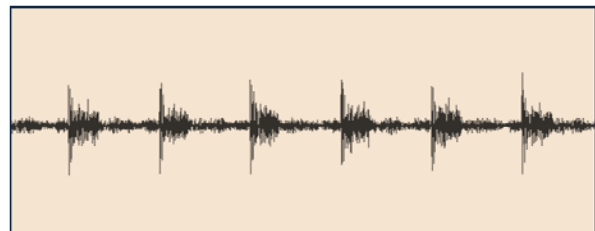
**Figure-3.** Characteristic waveforms after milling the workpiece using sharp ceramic milling cutter (a) and worn cutter (b).

The octave bond of vibration signal is shown in Figure-4. An increase of wear the level of vibration signal also increases in all represented octaves, especially in a 2000 Hz range, where the natural frequency of the milling machines is usually placed [5].



**Figure-4.** Octave bond of vibration signal after milling the workpiece using sharp ceramic milling cutter (a) and worn cutter (b).

The experimental data shown in Figure-5 shows that the amplitude of the vibration displacement impulse at the start time of contact between the milling cutter and machined material far exceeds its amplitude when the cutter goes out the cutting area. This impulse enhances the probability of brittle fracture, especially when using ceramic inserts.

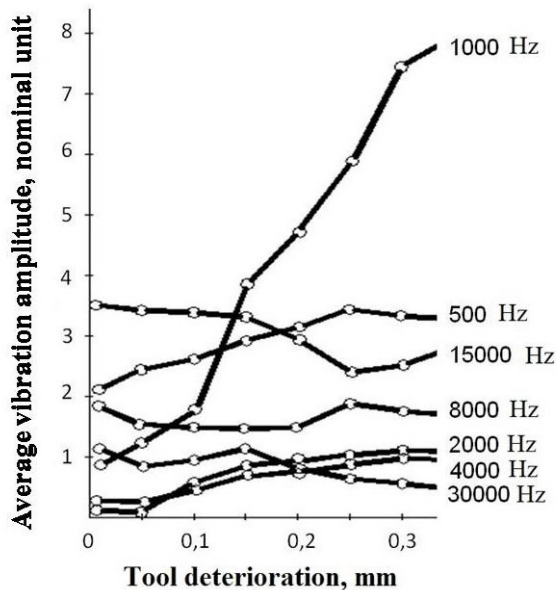


**Figure-5.** Characteristic impulses of vibration acceleration during milling using ceramic cutting tool with one sharpened tooth.

The line charts of vibration amplitude variation in various frequency domains for face milling using ceramic inserts with different wear are shown in Figure 6. It can be

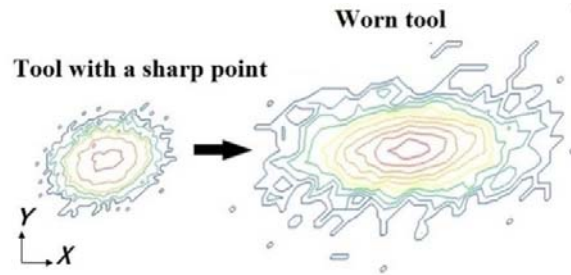


seen that in different octave bands the vibration amplitude behavior is ambiguous. Besides, entrance of cutter in cut leads to the manufacturing system stiffness increases, and when the cutter exits the workpiece the stiffness becomes lower that largely can be explained by a number of teeth involved in cut. That means that vibration signal is sensible to the depth of cut.



**Figure-6.** Variation of mean amplitude of vibrations of various frequencies with progressive worn of milling cutter equipped with ceramic inserts.

In Figure-7, a typical round chart looking like a windrose diagram is shown. It represents the results of hodograph recordings for vibration displacement of the ceramic insert tip basing on the accelerometers data in the XY plane. The results of experiments showed that the maximum amplitude variation is exactly in direction of the X axis. When passing from sharp cutting edge to worn one, the maximum vibration amplitude increases both in the X-axis direction (up to 2.6 times higher) and in the Z-axis direction (up to 2.2 times higher). The amplitude increase in the Y-axis direction is relatively low (about 35%). The unacceptable tool tip wear comes amid worsening the workpiece surface roughness. In that case, the characteristic variation of the vibroacoustic signal coming from the accelerometer is a consistent diagnostic indicator [6].



**Figure-7.** Amplitudes of vibration along X and Y axes with progressive worn of milling cutter equipped with ceramic inserts.

## SUMMARY

Consequently, the results of experimental studies performed at MSUT "STANKIN" and presented in this paper show the sensitivity of vibroacoustic signal to the cutting process parameters variation. In a number of situations, when finishing (precise machining) parts using ceramic cutting tool, the only way to receive information about the machining process and cutting tool condition is the vibration control. In particular, the cutting force measurement traditionally used for the manufacturing system diagnostics and monitoring may not be sensible to the process parameters variations, e. g. when one or more cutting teeth are broken, or when chatter arises during machining, or the cutting tool is extremely worn during finishing. The vibrations inside the cutting area may be the only available information providing a reliable machining process monitoring.

In addition, it is expressly understood that the cutting conditions variation leads in a complicated way to the change of vibration signal parameters. It makes difficult to predict those parameters without preliminary experimental study. It should be underscored that a variable stiffness of workpiece observed when machining a complex-shaped surfaces, exerts an additional influence on the vibration signal parameters. Thus, the implementation and use of the diagnostic system under production conditions must be based on the detailed preliminary theoretical and practical background and testing of innovative technologies.

## ACKNOWLEDGEMENTS

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